Long-term Global Morphology of Gravity Wave Activity Using UARS Data

Contract NAS5-98045

Quarterly Report
Mar 18, 2000 – Jun 18, 2000

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ABSTRACT

This quarter was largely devoted to a detailed study of temperature data acquired by the Cryogenic Limb Array Etalon Spectrometer (CLAES) on UARS. Our analysis used the same sequence of methods that have been developed, tested and refined on a more limited subset of temperature data acquired by the CRISTA instrument. We focused on a limited subset of CLAES temperature data during November, 1992, based on our reasoning that geographical and vertical trends in the small-scale temperature variability could be compared with similar trends observed in November 1994 by the CRISTA-SPAS satellite. Results, backed up with hindcasts from the Mountain Wave Forecast Model (MWFM), reveal strong evidence of mountain waves, most persuasively in the stratosphere over the Himalayas on 16-17 November, 1992. These CLAES results are coherent over the 30-50 km range and compare well with MWFM hindcasts for the same period. This constitutes, we believe, the first clear evidence that CLAES explicitly resolved long wavelength gravity waves in its CO2 temperature channel. A series of other tasks, related to mesoscale modeling of mountain waves in CRISTA data and fitting of ground-based and HRDI data on global scales, were seen through to publication stage in peer-reviewed journals.

A three-year research project funded by:

Office of Mission to Planet Earth
National Aeronautics and Space Administration
Washington, DC 20546.

NRA-97-MTPE-04 (Science Investigations in Support of the UARS Mission)

1. Work and Results this Quarter

1.1 Two-Dimensional Mesoscale Model Simulations of Stratospheric Mountain Waves over the Southern Andes

The previous quarter (section 1.1) we described the final stages of an extended modeling study, using a two-dimensional mesoscale model, to simulate stratospheric mountain waves over the southern Andes mountains, as gleaned from satellite temperature measurements from the CRISTA instrument on the CRISTA-SPAS satellite and the MLS instrument on UARS. The paper was copy edited and camera ready copy submitted for final publication in the AGU Monograph *Atmospheric Science Across the Stratopuase* [*Tan and Eckermann*, 2000]. Work was also expended this month on my editorial duties for this monograph.

1.2 Analysis of CLAES Temperature Profiles for Gravity Wave Perturbations

Detailed analysis of temperatures from the CRISTA instrument on the CRISTA-SPAS satellite has revealed clear evidence of gravity wave signatures, as has been developed and outlined at length in research reported in previous quarters. This quarter, we commenced a pilot to study to apply what we have learned from analysis of CRISTA temperatures to the Cryogenic Limb Array Etalon Spectrometer (CLAES) on UARS. We have done this because CLAES is an instrument similar in concept to CRISTA: like CRISTA, CLAES is a cryogenically cooled limb-scanning infrared spectrometer, acquiring spectra within a more limited range of 3.5-12.9 μm. Unlike CRISTA, which acquired full infrared spectra, CLAES uses a series of filters on a chopper wheel to isolate lines within specific narrow regions of interest [*Roche et al.*, 1993]. Nonetheless, like CRISTA, CLAES temperatures in the stratosphere and lower thermosphere were inferred from the CO_2 Q-branch emission at ~792 cm^{-1} (12.6 μm).

Gille et al. [1996] provided an extensive validation study of the CLAES temperature product. Comparisons with global analyses and radiosondes showed quite good agreement, with differences of ~2 K. *Gille et al.* [1996] estimated random statistical errors in Version 7 CLAES temperatures to range from ~0.9 K at 100 hPa (~16 km) to ~2.2 K at 0.46 hPa (~53 km). The vertical resolution of the profiles is ~2.5 km, giving a Nyquist vertical wavelength of ~5-6 km. While CRISTA temperatures are a little more accurate than this (estimated typically in the 0.5-1 K range), our analysis has revealed stratospheric gravity wave temperature perturbations as large as 10 K in the CRISTA data. Thus, on the basis of our experience with the CRISTA temperature data and the estimated random errors in CLAES temperatures, there seems good reason to believe that stratospheric gravity waves may be evident in CLAES temperature data, since the along-limb acquisition characteristics should be fairly comparable. Indeed, stratospheric Kelvin waves have been seen in equatorial CLAES temperatures [*Shiotani et al.*, 1997; *Canziani*, 1999].

Accordingly, we acquired a subset of the latest version (Version 8) CLAES level 3AT data from the Goddard DAAC. We concentrated on data from November-December 1992, since this period corresponds best to the November, 1994 period of the first CRISTA-SPAS mission. Since we have a good understanding of the global morphology of gravity wave temperature variance from this mission, it provides a good initial basis from which to analyze and interpret similar potential signals in CLAES temperatures.

In this spirit, we analyzed the CLAES temperature fields in exactly the same way that we analyzed the CRISTA data, fitting the full day's data using a wavenumber 0-6 Kalman filter, subtracting to leave a small-scale temperature residual, then analyzing residual temperature fluctuations using a Maximum Entropy (MEM) to locate wavenumber peaks, and harmonic analysis (HA) to delineate vertical variations in peak wave amplitude of these (this process was developed and described at length in previous reports). MEM/HA estimates at each altitude are stored and global maps for each day are plotted accordingly. This was a detailed task that took some time to set up and refine, and took up the majority of the research and analysis time for the project this quarter

Figure 1 shows temperature perturbation amplitudes $\hat{T}$ at 30 km altitude derived from the primary MEM/HA spectral peak in the CLAES temperature profiles acquired from UARS over a two day sequence starting November 16, 1992. Figure 2 shows a similar pattern of wave amplitude estimates from CRISTA on 6 November, 1994.

We note from Figures 1 and 2 that the geographical coverage of each instrument rather different in each case. This is caused by differences in the viewing geometry of each instrument. Unlike CRISTA, which was backwards viewing, CLAES viewed the limb at a 90° angle to the spacecraft orbital motion. Thus, it views the atmosphere farther north and farther south than CRISTA (to latitudes ~80°) in one hemisphere (depending on the yaw cycle), but has much more limited coverage of the opposite hemisphere (only to latitudes ~34°). The sampling characteristics are very much like those of the MLS instrument [see, e.g., *McLandress et al.*, 2000]. We see from Figure 1 that, on November 16-17, 1992, the UARS yaw cycle was such that CLAES preferentially viewed the Southern Hemisphere.

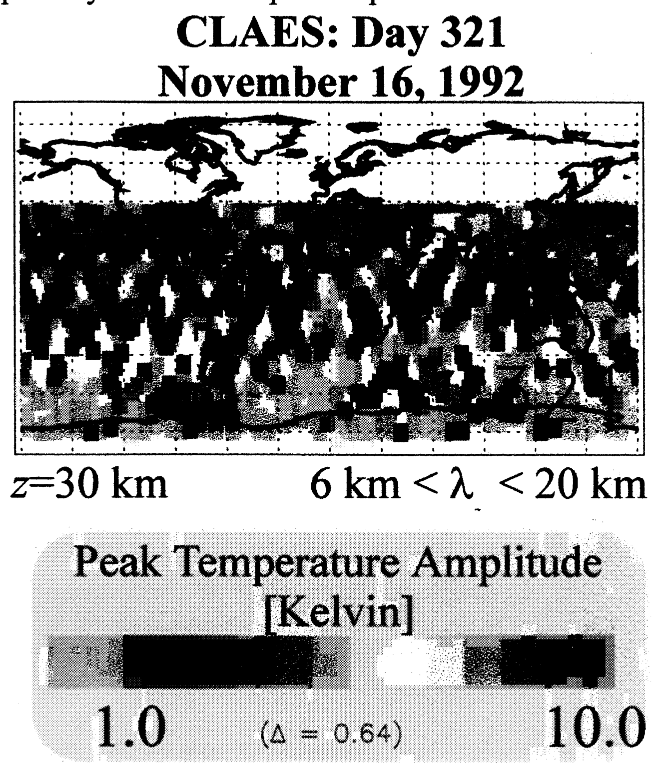

Figure 1: Global maps of gravity wave temperature variance from CLAES measurements at 30 km altitude for 2 days starting on Day 321 of 1992 (November 16-17), with results plotted for fluctuations in the vertical wavelength range between 6 and 20 km.

With these sampling differences in mind, we see qualitative similarities between the CLAES November 16-17, 1992 observations in Figure 1 and the CRISTA observations on November 6, 1994 in Figure 2. First, large regions of the stratosphere over the Southern Ocean have very small $\hat{T}$ values. In equatorial regions, however, typical ambient $\hat{T}$ values are somewhat larger.

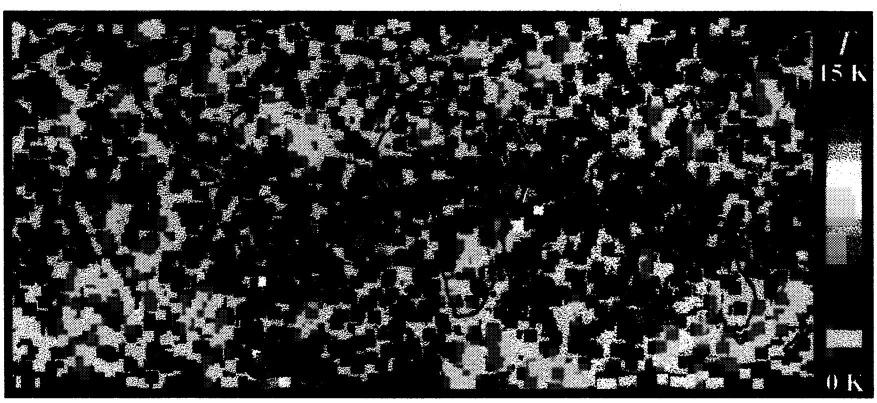

Figure 2: Global maps of gravity wave peak temperature amplitudes at 25 km inferred from CRISTA temperatures on November 6, 1994, after correction for observational "visibility" effects.

More apparent, however, is a large isolated region of enhanced activity located directly above the southern Andes. Extensive analysis outlined in previous reports and publications [*Eckermann and Preusse*, 1999] has definitely associated the CRISTA mesoscale temperature enhancement over the southern Andes in Figure 2 as due to a long mountain wave forced by flow across the Andes.

Also apparent in Figure 1, but less apparent in Figure 2, is a large cluster of large $\hat{T}$ values to the north of India. This is interesting since it corresponds to the high mountainous regions of the Himalayas. These regions of enhanced temperature amplitudes stand out from other regions at similar northern latitudes ~30°N, where much reduced $\hat{T}$ values are evident. All of this is strong (but preliminary and

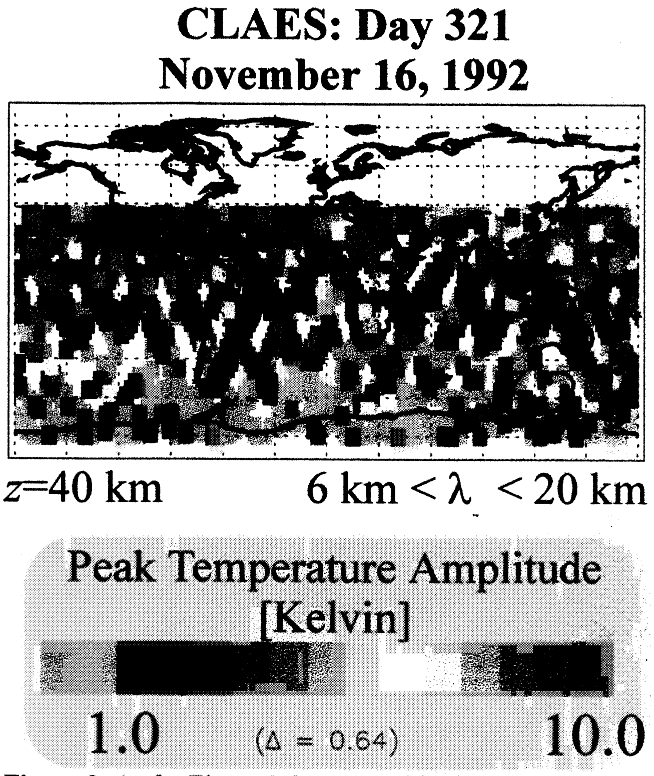

Figure 3: As for Figure 1, but at an altitude of 40 km.

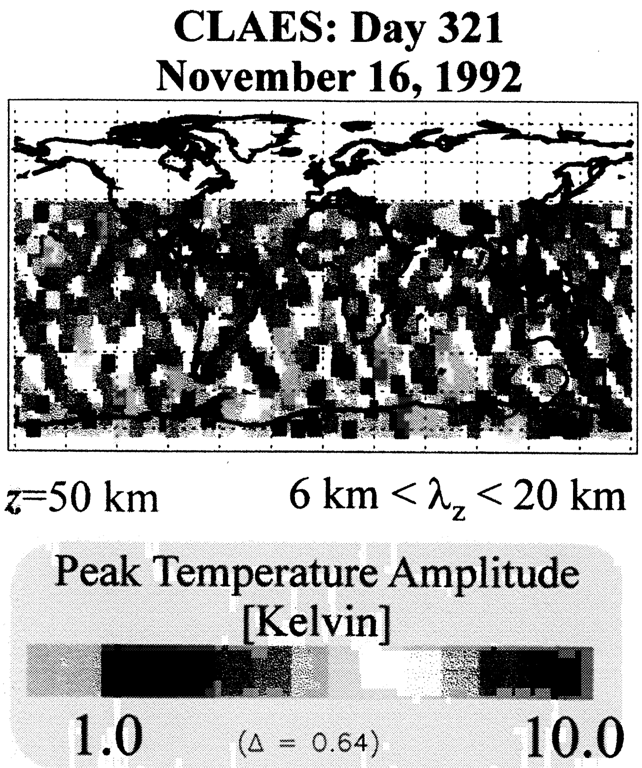

Figure 4: As for Figure 1, but at an altitude of 50 km.

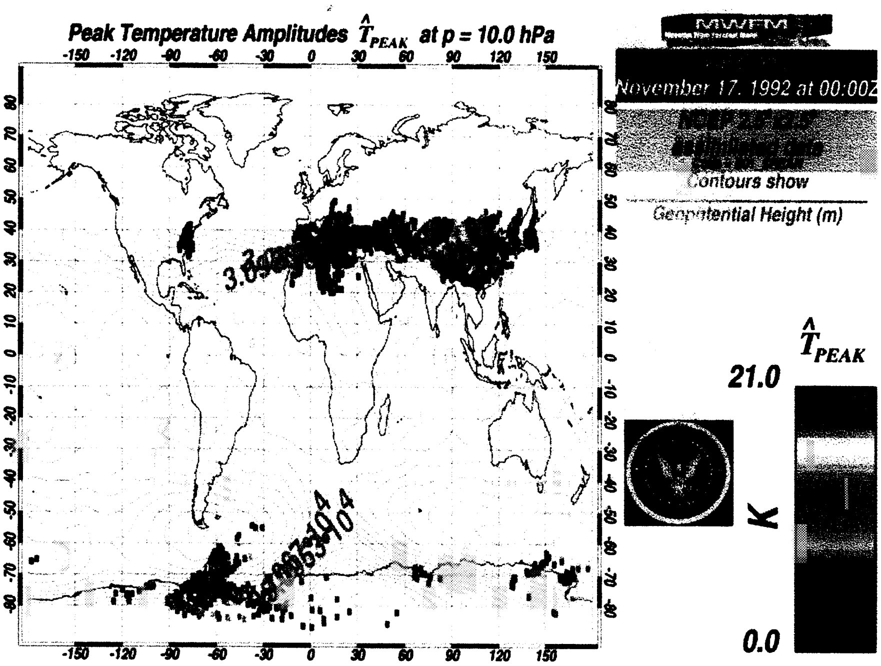

Figure 5: MWFM hindcast within the CLAES view area for southward UARS yaw cycle (~35°N-80°S) on November 17, 1992 at 0UT, at an altitude of 10 hPa (~32 km). Pink contours show geopotential height contours at this pressure altitude. This hindcast was constrained by the NCEP 2.5°x2.5° reanalysis fields for this time and date. Results were filtered to remove horizontal wavelengths > 100 km and vertical wavelengths > 5 km, to mimic the anticipated selectivity of the CLAES temperature data to long wavelength gravity waves.

non-definitive) evidence that there are the manifestations of long wavelength gravity waves radiated from these mountainous regions, which propagate into stratosphere and produce explicitly resolved temperature perturbations on CLAES temperature profiles.

To assess this, next we investigate the fluctuations in the CLAES data at higher altitudes in the stratosphere. If the fluctuations at 30 km in Figure 1 were due to a chance clustering of temperature errors in some profiles at 30 km, we might expect to see a somewhat different uncorrelated pattern 10 km higher at 40 km. Figure 3 shows the corresponding $\hat{T}$ estimates at 40 km. Figure 4 shows the corresponding $\hat{T}$ estimates at 50 km. The geographical distributions are very similar to that seen in Figure 1, which is inconsistent at least with random errors in CLAES temperatures that are uncorrelated in altitude, and consistent with a geophysical interpretation in terms of gravity wave amplitude trends that persist as waves propagate from 30 km to 40 km and then to 50 km in altitude.

To test whether these might be mountain waves, we conducted MWFM hindcasts for this period, based on recently issued 2.5°x2.5° NCEP global fields from the 40 year reanalysis project [*Kalnay et al.*, 1996]. We also conducted comparison simulations with DAO data for the period, which consisted solely of the coarser 5°x4° analysis fields. The results were basically comparable, though showed some differences which we ascribe to shortcomings in the cruder and older DAO assimilations, possibly in the troposphere. For present purposes, we use the NCEP analyses as our "best guess" for what the atmosphere was doing at this time.

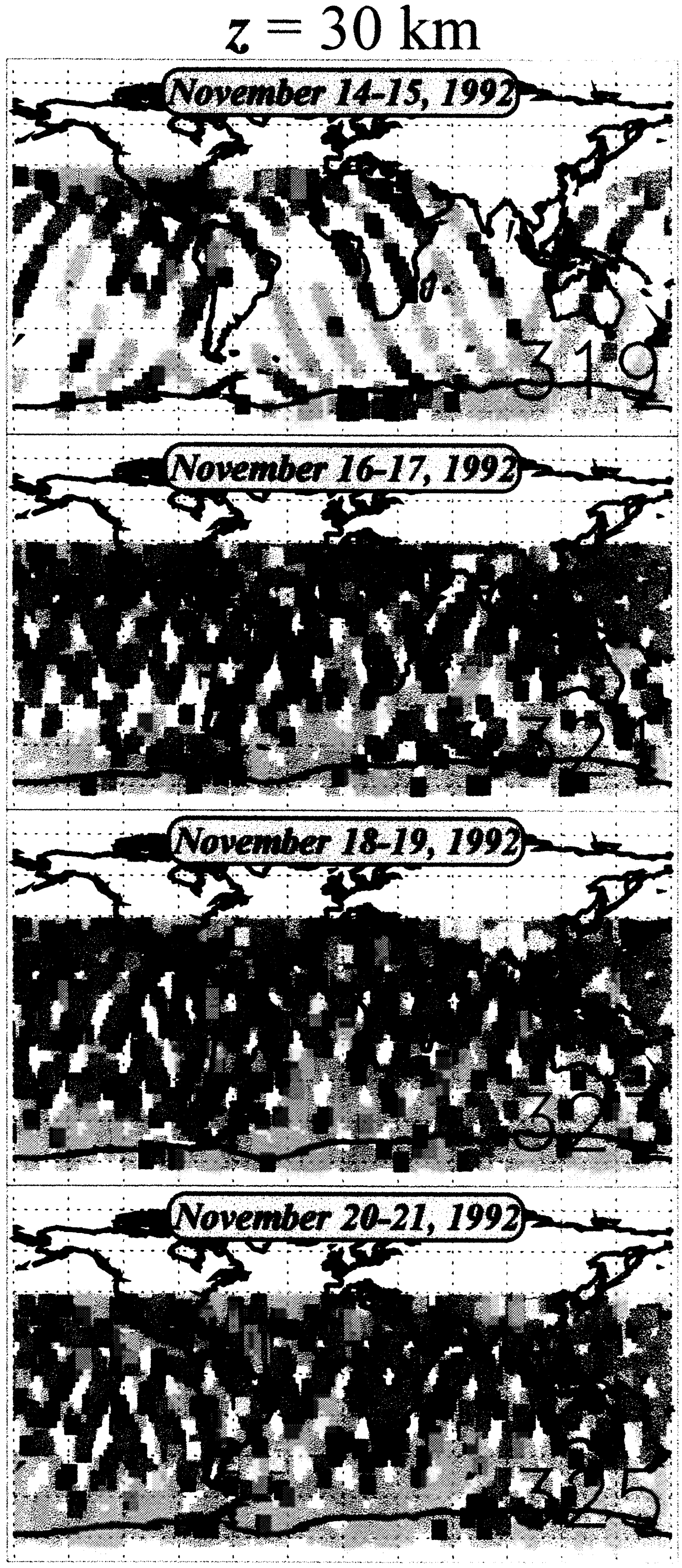

Figure 6: As for Figure 1, but showing a sequence of 2-day maps of CLAES $\hat{T}$ amplitudes at 30 km, from November 14-21, 1992 at an altitude of 30 km.

Figure 5 shows results from MWFM hindcast runs constrained by the NCEP reanalysis fields for 17 November 1992 at 0 UT, a time roughly at the center of the 2 day CLAES observation period November 16-17 (Figure 1). These hindcast simulations predict a concentration of enhanced mountain wave temperature variance in the stratosphere over the extended Himalayan Region, much as observed in Figure 1 and at higher altitudes in Figures 3 and 4. Further, other mountainous regions at a similar latitude, such as the Rocky Mountain Region over the western USA, produces no detectable gravity wave variance, again much as observed in Figures 1, 3 and 4. The absence of gravity waves here in both model predictions and data is, in some ways, even more persuasive, since it agrees with what we know about mountain wave propagation: i.e., on November 16, 1992, MWFM/NCEP hindcasts suggest that mountain waves could freely propagate into the stratosphere with long wavelengths over the Himalayas, where they could be detected by CLAES. Conversely, mountain waves are either not strongly forced, are blocked from propagating into the stratosphere, or have wavelengths too small to be resolved by CLAES, and should not be detected. Thus, detection over the Himalayas and non-detection over the western USA, as simulated and observed, is, in a sense, double confirmation that this activity over the Himalayas in CLAES temperatures is a real believable gravity wave signature.

There are, however, some discrepancies also. For example, the isolated peak over the southern Andes, evident in Figures 1, 3 and 4, does not show up in the hindcast in Figure 5. Hindcasts for other times and days, and in which wavelength filtering was not applied to the hindcast output, did reveal an occasional small isolated peak over the southern Andes, but usually of fairly small amplitude (not shown). To study this a bit more, Figure 6 shows results a sequence of CLAES $\hat{T}$ plots at 30 km for the day pairs immediately before and after those shown in Figure 1 (which is reproduced in the second panel from the top in Figure 6). The sampling on the preceding days (top panel) is a little sparse globally, so it is hard to discern trends on the days prior. For the days afterwards (bottom two panels in Figure 6), however, we see that we have better global coverage in the CLAES data. These plots show that the extended region of activity over the Himalayan Region persists and evolves somewhat over the following four days (18-21 November, 1992), giving us further confidence in the fidelity and geophysical reality of this patch of variance in the CLAES temperature data.

The "peak" over South America, however, is much more fickle and does not seem to persist as strongly with time in Figure 6. Assuming it is real (i.e. geophysical), there are several plausible reasons for explaining how such waves might arise in the CLAES data but not be simulated by the MWFM hindcasts. One possibility is weaknesses in the assimilated data being used. Since these fields are reanalyses based on assimilated data acquired about a decade earlier, they may not accurately simulate fine scale flow features in and around this region of the far southern Andes that may be important for the forcing and propagation of long mountain waves into the stratosphere at the time. Another plausible reason may be that the MWFM algorithms may have weaknesses here. Many processes may be important for forcing mountain waves in this region, but are ignored currently by the simplified analytical parameterization algorithms at the core of the MWFM. One potentially important effect is time dependence of the background wind conditions. MWFM (as with most mountain wave schemes) assumes a time-independent background atmosphere, whereas, in fact, wind conditions tend to vary considerably as a function of time as weather systems move across the topography and evolve. Modeling studies [e.g., *Lott and Teitelbaum*, 1993] and observations [e.g., *Ralph et al.*, 1997] show the radiation of nonstationary waves, which can propagate into regions that stationary wave theory would forbid them to enter. To the limited extent that nonstationary mountain waves are understood or have even been modeled, it appears that sudden time dependence of an evolving wind system will radiate a transient "burst" of nonstationary lee waves into the atmosphere. As the atmosphere settles into a new quasi-steady state, stationary lee waves reemerge. The activity in Figure 6 is (qualititatively) reminiscent of this nonstationary burst scenario, and may explain why MWFM hindcasts in Figure 5 do not capture it. Other explanations are of course possible: other omitted effects such as low-level nonlinearity, blocking and surface friction [e.g., *Leutbecher and Volkert*, 2000] could all be potentially significant.

1.3 Self-Consistent Space-Time Synthesis of Mesospheric Temperature Data from HRDI and Ground-Based Instruments

As outlined in last quarter's report, we devoted some effort to developing a new model which combines both UARS data (in our test cases, HRDI temperatures) with data from ground-based instruments. This improves the overall space-time sampling characteristics – in particular, the ground-based data have far better local time coverage, whereas the slow precession of the UARS spacecraft through local time leads to much poorer local time coverage, which makes extraction of tides in particular problematic. In collaboration, we worked on a new model for self consistently combining both UARS and ground-based datasets together using a Fourier fitting algorithm, which takes into account the precise space-time sampling patterns of each instrument. The fit, which allows for mean biases and a range of wave motions, makes it easier to identify tides and potential quasi-stationary planetary Rossby waves in the datasets.

The bulk of the research work was completed and briefly outlined last quarter. This quarter we completed the effort by completing and submitting a paper on the method and findings to *Geophysical Research Letters* [*Drob et al.*, 2000]. The paper was accepted for publication and we worked towards the end of the quarter on generating final electronic camera-ready copy of the accepted paper for publication in the journal.

2. Analysis

2.1 Interpretation of Results Obtained to Date

As recommended last month, this month we undertook a major drive to study the raw level 3AT temperature data from the CLAES instrument, focusing on a selected subset that allowed us to compare results more easily and immediately with what we have learned from the CRISTA dataset. The initial results, set out in section 1.2, show quite compelling preliminary evidence that CLAES temperature data do indeed resolve long gravity waves. In particular, much of the enhanced clustering of high $\hat{T}$ values in Figure 1,3,4 and 6 appear to be manifestations of mountain waves. The strongest evidence, based on a series of targeted Mountain Wave Forecast Model (MWFM) hindcasts (one of which is shown in Figure 5), centers on an extended region of activity spread throughout the depth of the stratosphere overlying the Himalayas, on or around November 16, 1992. The excellent visual correlations among the measured peak temperature amplitudes and those hindcasted by the MWFM gives us good reasons to believe that this activity is indeed long wavelength mountain wave activity in the stratosphere radiated by flow across the Himalayas.

These are exciting results. While gravity waves have been isolated in MLS data and there has been evidence of gravity wave signals in some of the higher altitude airglow data, to our knowledge gravity waves have not been detected in data from other UARS instrument. This study, motivated by the similarity of CLAES temperatures to those acquired by CRISTA, and further spurred by some conversations with Dr. John Mergenthaler of the CLAES team that they had seen interesting wiggles in temperature data near the Andes (similar to those found in CRISTA), has, we believed, started to confirm that gravity waves are indeed resolved explicitly by the CLAES temperature channel (level 3AT data).

2.2 Recommended Further Action

These exciting initial results for the CLAES temperature data have convinced us that we should continue studying these effects in more depth in the coming quarter. What we plan to address next is a new subset of CLAES data during a northward looking yaw cycle. Such data were acquired during December, 1992 and cover latitudes from ~34°S to ~80°N. Thus, we may see higher latitude mountain wave effects in these northern hemisphere data, perhaps along the lines of the stratospheric mountain waves over central Eurasia that we saw clearly in the CRISTA data on November 9, 1994 [*Eckermann and Preusse*, 1999]. Depending on what we see in these data, we shall also attempt, as we did this quarter, to back these data up with targeted MWFM hindcast runs, to see if other mountain wave effects might be evident.

A new push this quarter will also be to start a full and methodical writeup of the gravity wave analysis and products we have developed and issued during our long-term analysis of temperature data from the CRISTA instrument. The impetus for this is the announcement of a special issue of *The Journal of Geophysical Research* devoted to results from the first, and new results from the second, CRISTA-SPAS mission. We believe this provides an appropriate forum to discuss in depth our analysis of gravity waves in these data. Work to this end will commence in the next few weeks.

2.3 Relation to Ultimate Objectives of the Research Contract

The CLAES results obtained this month, outlined in section 1.2, represent another significant milestone of the project that directly addresses some of the key initial objectives of this research contract. In broad terms, a key goal was to assess the extent to which the instrument suite on UARS explicitly resolved, measured and defined gravity waves in the stratosphere and mesosphere. While our analysis in many earlier quarters has focused more on data from the CRISTA instrument on the CRISTA-SPAS satellite, it has this quarter yielded the payoff that we had always hoped for, and had argued for in the original proposal – that detailed analysis of the limited set of high-resolution CRISTA data would provide important insights into how gravity waves might be resolved in the much larger datasets acquired by the suite of UARS instruments. The work has transitioned extremely nicely to CLAES, since the two temperature products (CLAES and CRISTA) are equivalent in most important respects. The only difference of note is the different viewing angle for each instrument which, apart from yielding different geographical coverages for each instrument (see Figures 1 and 2), does not lead to a significantly different gravity wave detection in general. The results are also key, in the sense that CLAES, while acquiring a limited set of data within the UARS context (1992-1993), actually acquired a great deal m ore data than CRISTA did in it's two week-long missions. Thus, in future quarters, if these initial trends hold up, CLAES may allow us to study waves in temperature data in a much more long-term way than was possible with CRISTA. Our upcoming goals were outlined in section 2.2 above.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	18 Jun 00	Interim (quarterly): 18 Mar 00 – 18 Jun 00

4. TITLE AND SUBTITLE
Long-term Global Morphology of Gravity Wave Activity Using UARS Data

5. FUNDING NUMBERS
C - NAS5-98045

6. AUTHORS
Stephen D. Eckermann

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Computational Physics, Inc., 2750 Prosperity Avenue, Suite #600, Fairfax, VA 22031

8. PERFORMING ORGANIZATION REPORT NUMBER
5090-10

8. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration, 300 E Street SW, Washington DC 20024-3210

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
mountain waves, gravity waves, space, satellite, stratosphere, temperature

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	

NSN 7540-01-280-5500

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STANDARD FORM 298 (Rev 2-89)
Prescribed by ANSI Std 239-18
298-102

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